Presented at the U.S. DOE Solar Energy Technologies Program Review Meeting, Denver, CO, Nov. 7-10, 2005.

Simplified Hybrid Process: Application to Normal, Sub-micron, and Light-trapping CIGS Devices

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ABSTRACT

This paper summarizes the progress made by Energy Photovoltaics, Inc. ("EPV") in CIGS photovoltaic technology during the past year. Three main results are described: (1) development and optimization of EPV's second-generation simplified hybrid process for CIGS deposition involving both sputtering and evaporation; (2) development of sub-micron CIGS devices and modules, and (3) production of a new back reflector layer (TiN) by hollow cathode sputtering. These achievements have increased CIGS throughput, reduced In consumption, and paved the way to ultra-thin, light trapping CIGS devices and modules.

1. Introduction and Objectives

While thin-film $Cu(In,Ga)Se_2$ has always held great promise for photovoltaics, CIGS modules have yet to contribute in a significant way to renewable energy production. This project aims to provide an existence proof that both CIGS material (of high quality over a large area) and CIGS modules (of good efficiency) can be produced in a robust and reproducible manner, and with processing and module characteristics based on which cost-effective commercial module manufacturing could be projected. This undertaking is consistent with the goals of the Thin-Film Photovoltaics Partnerships Program (TFPPP), including the acceleration of thin film solar cell and module development, and the attainment of 12% thin-film modules by 2007 [1].

2. Technical Approach

EPV has chosen to develop glass-based CIGS power modules produced by the well-proven vacuum deposition approach. All depositions are conducted from linearly extended sources onto moving substrates. In 2002 EPV reported the hybrid process for CIGS preparation, in which the Cu is supplied by magnetron sputtering, and the remaining elements (In, Ga, Se) are supplied by linear thermal sources. The hybrid process is notable for offering good Cu control, being easily scaled, and for having several features in common with the NREL three-stage process. NREL-verified efficiencies of 13.1% (cell) and 7.5% (26W module) were achieved with the hybrid process implemented in our large area systems (coating width of 44 cm) [2]. It was realized, however, that the process was not suitable for cost-effective manufacturing because of processing complexity. The development of a simplified process therefore became an imperative.

Another issue stood out as requiring consideration: the steeply rising costs of In and Se. This becomes a strategic issue if future, multi-GW module production is contemplated. To address the In resource issue, we have made the development of CIGS devices and modules having an absorber layer of sub-micron thickness (as opposed to 2.5µm) a further objective of this work. At these thicknesses, the smaller absorption coefficient of CIGS at long-wavelengths does not allow full optical absorption in a single pass and J_{sc} is reduced. The utilization of light trapping techniques should allow J_{sc} to be restored. One of the needs, then, is a back contact layer with a much higher IR reflectivity than that of Mo.

3. Results and Accomplishments

This year we successfully developed a second-generation (or simplified) hybrid process. This process considerably decreases the processing time and dramatically increases the throughput of CIGS absorber production. The process also intrinsically reduces the per-run consumption of Se.

Development and optimization of the simplified hybrid process was conducted in an R&D scale system. We have further applied the simplified hybrid process to the

Table I. Device performance w. simplified hybrid process

Sample	CIGS t (µm)	V_{oc} (mV)	FF (%)	J_{sc} (QE) (mA/cm^2)	Eff. (%)
H051205-8	0.74	590	70.5	29.1	12.1
H052005-1	0.82	605	67.9	29.4	12.1
H052305-5	0.85	608	70.5	27.9	12.0
H052405-6	0.91	638	70.0	28.7	12.8
H080205-4*	1.3	598	68.6	34.4	14.1

* with AR coating, all others do not have AR coating.

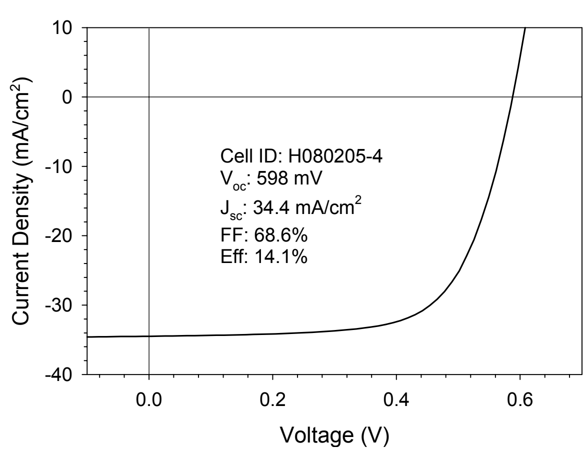

Fig. 1. J-V curve of a 1.3 µm CIGS cell.

production of sub-micron CIGS, and we are now able to fabricate devices with efficiencies of 12%-13% with a CIGS absorber thickness in the range of 0.75-0.90 µm. Table I lists the J-V parameters of some of these devices. CIGS film thicknesses were determined using a Dektak II stylus profilometer, and were confirmed by SEM measurement. Devices over 14% in efficiency have also been fabricated; the J-V curve of a 14.1% 0.4 cm^2 cell with a CIGS thickness of only 1.3 µm is shown in Fig. 1.

From Table I, it can be seen that when the CIGS layer is of sub-micron thickness, V_{oc} and FF are preserved and that only the previously-discussed drop of J_{sc} limits device efficiency. An alternative, stable, back contact layer with higher reflectivity than Mo is required to enhance optical reflection at the back electrode/CIGS interface and thus increase light absorption and J_{sc}. We have produced high quality titanium nitride (TiN) thin films by reactive-environment, hollow cathode sputtering (RE-HCS) and have shown that such films are suitable for this application. The films are gold colored and have a resistivity around 50-60 µΩ-cm. The reflectivity of TiN films with different thicknesses overcoated on Mo, and of Mo as a control, are shown in Fig. 2. The IR reflectivity of TiN is considerably higher than that of Mo. In a first device in which 2.5µm CIGS was deposited (courtesy IEC) onto a TiN back electrode, 11.7% efficiency was achieved (V_{oc} 551mV, J_{sc} 30.8 mA/cm^2, FF 69.0%).

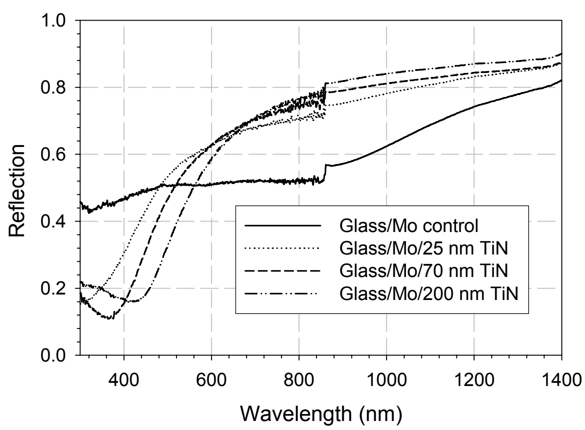

Fig. 2. Total reflectance of TiN/Mo and Mo films

CIGS modules with micron and sub-micron thickness were also produced in EPV's pilot line. The main purpose was to find out if there are any additional problems with ultra-thin CIGS module processing. The performance of modules with CIGS thickness 1 µm and 0.75 µm was found to be not much inferior to that of modules with a normal thickness of 2.5 µm. The results for these modules are listed in Table II. We see that the FF and V_{oc} per cell for thin CIGS are essentially unchanged from those obtained at 2.5µm, while, as expected, the J_{sc} is reduced. So far, we have not observed any additional problems (such as shunting) in the I-V behavior with reduced thickness of CIGS down to 0.75 µm.

Table II: Physical and J-V parameters of CIGS modules

Module (#cells)	*CIGS th.(µm)*	*Area (m^2)*	*V_{oc} (V)*	*I_{sc} (A)*	*P_{max} (W)*
A (71)	2.5	0.345	38.5	1.20	26.0
B (71)	1.0	0.330	37.7	1.01	21.1
C (34)	0.75	0.134	18.6	0.80	8.48
		FF (%)	*V_{oc} /cell*	*J_{sc}[1]*	*Eff (%)*
A (71)	2.5	56.4	0.542	24.7	7.52
B (71)	1.0	55.7	0.531	21.8	6.41
C (34)	0.75	57.0	0.547	20.3	6.32

[1]*aperture area basis (mA/cm^2)*

4. Conclusions

During 2005, EPV developed a simplified hybrid process for CIGS combining sputtering and linear thermal sources. The simplified process has considerably reduced CIGS processing time. A device efficiency of 14.1% was achieved at a CIGS thickness of 1.3µm, and 12-13% at sub-micron thicknesses in the range 0.75 – 0.90 µm. Fabrication of sub-micron CIGS modules was also carried out. Upon thinning the CIGS from 2.5 to 0.75 µm, a loss in module efficiency of only 16% was found, stemming solely from loss of J_{sc}. The potential back contact material TiN was prepared by RE-HCS. It was shown to have considerably higher IR reflectivity than Mo, and hence should increase light absorption in ultra-thin CIGS devices. A first trial of TiN as a back contact showed it to be both adequately stable and ohmic, and 11.7% devices were prepared. These represent important steps towards ultra-thin, light trapping CIGS devices and modules.

ACKNOWLEDGEMENTS

The authors thank R. Saramak, R. Zhang, J. Cambridge, A. Foustotchenko, and R. Lyndall of EPV for their contributions, W. Shafarman of IEC for reflectivity measurements, and R. To and M. Al-Jassim of NREL for SEM analysis. This work was partially supported by the US DOE under subcontract ZXL-5-44205-05 with NREL.

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